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Resource Requirements Planning for Hospitals Treating Serious Infectious Disease Cases

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Abstract

This report presents a mathematical model of the way in which a hospital uses a variety of resources, utilities and consumables to provide care to a set of in-patients, and how that hospital might adapt to provide treatment to a few patients with a serious infectious disease, like the Ebola virus. The intended purpose of the model is to support requirements planning studies, so that hospitals may be better prepared for situations that are likely to strain their available resources. The current model is a prototype designed to present the basic structural elements of a requirements planning analysis. Some simple illustrative experiments establish the model's general capabilities. With additional investment in model enhancement and calibration, this prototype could be developed into a useful planning tool for hospital administrators and health care policy makers.

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NOMENCLATURE

ED	Emergency Department
EHC	Emory Healthcare
ER	Emergency Room
EUH	Emory University Hospital
EUSOM	Emory University School of Medicine
EVD	Ebola virus disease
HEPA	High-efficiency particulate air
ICU	Intensive care unit
ID	Infectious disease
PPE	Personal protective equipment
PAPR	Powered air purifying respirator
SARS	Severe acute respiratory syndrome
SCDU	Serious communicable disease unit

1 INTRODUCTION

The current Ebola outbreak has created concern among public health officials, as well as considerable anxiety among elected public officials, about the ability of hospitals to treat serious infectious diseases that threaten to become epidemic. It is clear that treating patients with such diseases is very expensive and isolating such cases to prevent spread of the disease places significant strain on a hospital's facilities and staff. There is well-placed concern with the *resilience* of hospitals – the ability of these systems to withstand, adapt to, and recover from the effects of a disruptive event – in this case, an influx of patients with very specialized and resource-intensive care needs.

A resilience analysis framework has been defined by Vugrin *et al*. (2011) that involves three related capabilities – providing *absorptive capacity* so that the system can withstand disruptions, providing *adaptive capacity* so that services can be provided using alternate resources or processes, and providing *restorative capacity* so that recovery from a disruptive event can be accomplished quickly and at reasonable cost. The focus of this paper is on resource requirements analysis for a hospital faced with treating a set of patients who have a serious infectious disease (using Ebola Virus Disease (EVD) as the illustration). Resource requirements analysis attempts to determine what resources may be needed and what adaptation strategies can be followed to allow the hospital to absorb and adapt to the situation without compromising care for other patients.

2 A MODEL STRUCTURE FOR THE ANALYSIS

The basis of this analysis is a planning model expressed as a mathematical optimization. This model represents the resource availability and adaptive capacities a hospital leverages to care for patients, even when stressed by an outbreak of a serious infectious disease. The full mathematical formulation of the model is presented in the Appendix, but in this section we describe the fundamental ideas on which it is based, as well as the specific elements defined for the infectious disease analysis. The model is based on six types of entities: *patients*, *services*, *functions*, *resources*, *utilities* and *consumables*. These entities are related in a hierarchical way as shown in Figure 1. Patients are treated by services, and these services depend on functions, resources, utilities and consumables. Each level in the hierarchy supports (either directly or indirectly) all of the levels above it.

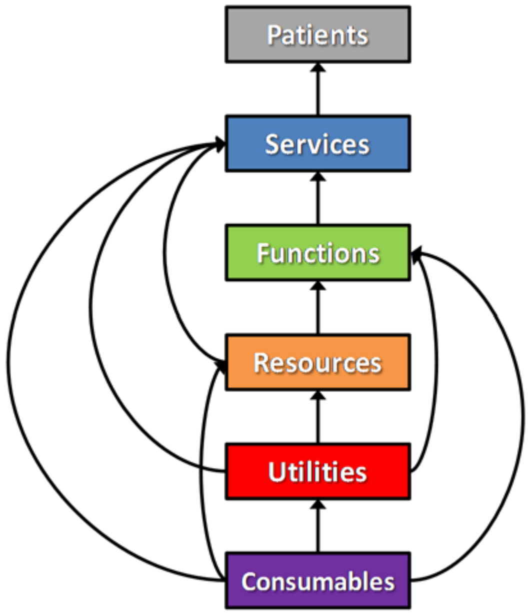

Figure 1. Hierarchical relationships among hospital entities.

Patients are divided into categories, each of which may have different care requirements and, thus, require different services. Services directly support patient care and consist of hospital activities provided by various hospital departments. The next level down in the hierarchy, functions, directly supports services. Functions include medical procedures for individuals and non-medical activities that contribute to patient care. Resources, utilities, and consumables are the tangible commodities, equipment, and people required to perform functions and services. Resources and consumables differ in that resources are reusable and consumables are not; i.e., after one use, a consumable good is "consumed." Consequently, depletion and replenishment of consumable stocks are important within the model. Utilities are a special class of resource that includes water, electricity and communications. Utilities consist of resources and services that are provided by external companies and are typically considered to be available in an essentially unlimited supply (under nominal conditions).

At the four lowest levels of the hierarchy, there are substitution possibilities. For example, a function may be provided using different resources, and those resources may require varying use of utilities and consumables. The model is designed to allow a user to specify a disruption (e.g., arrival of a patient in the Emergency Room showing signs of possible EVD) at a given time, and trace the adaptations (and associated resource use) as the hospital staff work to maintain appropriate care levels for the various categories of patients. The hospital may or may not have a facility identified as a Serious Communicable Disease Unit (SCDU). If a SCDU is not present, the EVD patient is accommodated within an Intensive Care Unit (ICU), and all other patients in that ICU must be moved to other locations in the hospital. This is an illustration of a form of adaptation (and resource substitution) within the modeled system.

If an SCDU is present, its characteristics and operation are based on the description of the unit at Emory University (Emory Healthcare, 2014). The following excerpt from the Emory document (from pp. 10-11) is very useful as background for many of the elements that have been included in the model:

> The Unit has been designed so that patients with any known infectious disease can be cared for in an environment that is safe for health care workers, other patients and the community at large. The Unit contains three patient care rooms, each entered only through an anteroom. Air in the three patient rooms is under net negative pressure in relation to the surrounding areas, with all airflow going from the hallway to the anterooms to the patient rooms. Air in the patient rooms has a laminar air flow across the patient bed. All air from patient rooms undergoes high-efficiency particulate air (HEPA) filtration before being 100% exhausted to the outside. The outside exhaust is geographically separate from any hospital air intake locations, and is high enough to allow for dilutional disbursement. The patients cared for in the Unit will span a wide range of clinical illnesses, from asymptomatic to critically ill. Because of this potential, the Unit has been designed to deliver a level of care that can equal that of any of the hospital's intensive care units. Each room is also plumbed for dialysis. The Unit has a certified biosafety cabinet for specimen processing in a dedicated laboratory and an autoclave for processing of waste generated. Patients will preferentially be admitted to the Unit directly from the outside through an external door that opens directly into the Unit. When entry through this door is not possible, the patient will be admitted through the exterior hospital doors opening onto the back of the hospital.
>
> The staffing for the Unit is provided by physicians who are members of the Infectious Diseases Division at the EUSOM, experienced EHC nurses who have received special training in the care of patients with serious communicable diseases and laboratory technologists. Specialty care is available through the specialty services at EUH. All personnel who directly care for the patient in the Unit receive intensive training on management of the patient and all PPE and infection control measures. As patients may be contagious prior to admission to the Unit, the Grady EMS Biosafety Transport Team, which has specially trained personnel and with whom this unit has planned and exercised since inception, will transport all patients to the unit. This team is on-call 24 hours a day, 7 days a week, and is capable of responding to a call for scheduled transportation from anywhere in Georgia. Their ambulance has been modified for ease of disinfection following patient transport.
>
> Patients presenting to an EHC ED with symptoms of any serious communicable disease will immediately be isolated in a private room within the ED until positive testing can be completed. If the patient is positive for a serious communicable disease, the specially trained nurses of this Unit will respond to aid in care and transportation of the patient.

The SCDU is designed to provide treatment for several types of serious infectious diseases in addition to Ebola, including brucellosis, pneumonic plague, SARS, etc.
For the current infectious disease (ID) analysis, seven categories of patients are defined:

EVD patients:	active Ebola cases being treated in the hospital
ICU patients:	non-Ebola patients that require ICU-level care
Other in-patients:	patients being treated in the hospital who do not require ICU or SCDU level care.
ER-High Risk EVD:	patients seeking medical attention in the Emergency Department (ED) who have a high risk for EVD (based on symptoms, travel history, etc.)
ER to ICU:	patients seeking medical attention in the ED who will require admission to an ICU in the hospital
ER -- Admitted:	patients seeking medical attention in the ED who will require hospital admission, but not require ICU-level care
ER -- Released:	patients seeking medical attention in the ED who have ailments not requiring hospital admission

The three categories of in-patients (EVD, ICU and Other) all draw on the same staff resources at the hospital, and may also have interacting demands for facilities (e.g., for ICU space if an SCDU is not available). The four categories of patients in the ER are included separately because they are treated using the same ED resources.

Patients are supported by 11 services, as follows:

- ER EVD Diagnosis
- ER Service
- Rapid EVD Testing
- EVD Care
- EVD Patient Lab Tests
- EVD Patient Imaging, EKG, Dialysis, etc.
- EVD Waste Removal
- EVD Patient Transport
- ICU Patient Care
- General In-patient Care
- Activate EDV Treatment

Separating the service ER EVD Diagnosis from ER Service allows the diagnosis of suspected EVD cases in private rooms within the ER, as well as use of PPE, etc., not associated with treating the rest of the ER patients. Rapid EVD Testing requires special treatment of samples by the hospital laboratory, and is invoked for high risk patients in the ER.

EVD patients require services that are not self-contained in the SCDU (if present). Examples may include EKG's, ultrasound exams, dialysis, etc. Providing these services (either within the SCDU or in an ICU dedicated to EVD patients) requires special procedures to avoid contaminating the equipment, as well as minimizing the potential exposure of technicians.

The EVD Waste Removal service allows us to associate special requirements and resources to the process of handling wastes from EVD patients. Transport reflects the special service required to transport an EVD patient for transfer to or from another medical facility, if such movement is necessary.

ICU Patient Care and General In-patient Care are aggregated services representing the array of activities normally required to treat those categories of patients. These services require a range of resources, including physicians, nurses, technicians, equipment, etc. The presence of these services in the model allows representation of the competition for resources among different categories of patients.

The final type of service, “Activate EVD Care”, allows some resources to be attached to the process of having one or more EVD patients in the hospital. These resource requirements may not vary with the number of patients, but switch “on” or “off” based on whether there is some patient in that category or none.

These services, in turn, require functions, resources, utilities and consumables. The utilities are line power, back-up generator power and water. At present, the following sets of functions, resources and consumables are used:

Functions	**Resources**	**Consumables**
SCDU Care	ID Physicians	High-Level PPE Sets
ICU Care	Critical Care Physicians	Step-Down PPE Sets
SCDU Lab Operation	Nephrologists	EVD Linens
Hospital Lab Operation	ER Physicians	EVD Cleaning Supplies
	EVD Team Nurses	EVD Other Materials
	EVD Team Lab Techs	EVD Waste Packaging
	ER Nurses	Generator Fuel
	ER Staff Techs	
	Other Nurses	
	Technicians/Equipment	
	Biosafety Transport Unit	
	Environmental Services Staff	
	SCDU	
	ICU	
	ED Private Room	
	Autoclave	
	PAPR Units	
	SCDU Dedicated Lab	
	Hospital Lab	

Most of the resources used in the analysis are staff resources, because they are likely to be most critical in treating EVD patients, as well as other patient categories. The differentiation between high-level and step-down PPE sets corresponds to the definitions given in Appendix 3 of the Emory document (Emory Healthcare, 2014, page 34). The biosafety transport unit definition includes the EMS personnel and the special ambulance that are part of that unit. The autoclave is used for disinfection of waste before disposal. The PAPR (powered air-purifying respirator) units are used together with the PPE sets, but are a non-disposable resource, rather than a consumable. The list of consumables, as well as defining EVD Waste Removal as an identifiable service, allows tracking the quantity of wastes from EVD patients if that presents itself as an issue of concern.

3 An Illustrative Analysis

To demonstrate use of the model, we consider a medium-sized hospital with an average total in-patient population of approximately 100 patients. In the specific scenario created for the test runs, the in-patient population over a 7-day period (21 8-hour time periods in the model) is as shown in Figure 2. There is more volatility in total patient population during the first three days of the week, and then the patient population is quite steady over the remainder of the week. We emphasize that this is a notional analysis, designed to demonstrate the model's capabilities, and does not correspond to any specific week in any particular hospital.

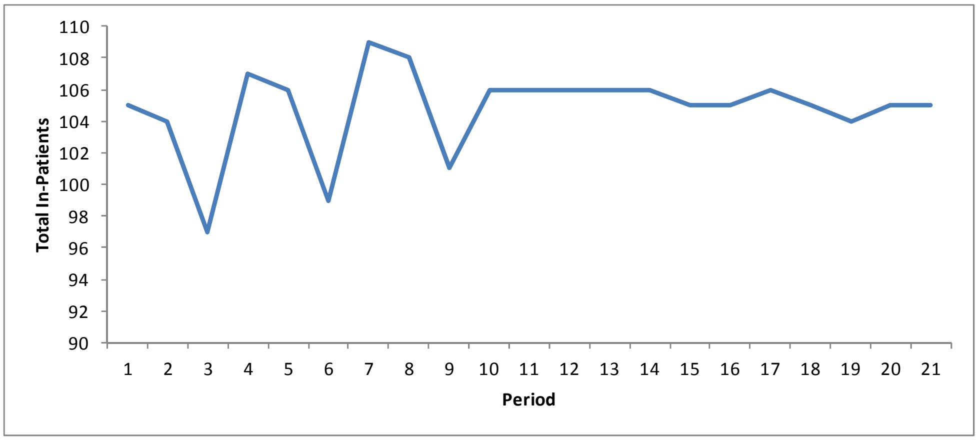

Figure 2. Total in-patient population during the first week of the test runs.

Of the total in-patients, 8-10 are in intensive care units (ICUs) in the hospital. The ICU patient population over the first week of the analysis is shown in Figure 3. For these experiments, we assume the hospital has no dedicated SCDU, so an EVD patient, if one presents for treatment, would have to be cared for in an ICU. This would mean moving other intensive-care patients out of that unit, and either accommodating them in another ICU or moving them to regular medical units, with resources being reassigned to provide them with adequate care.

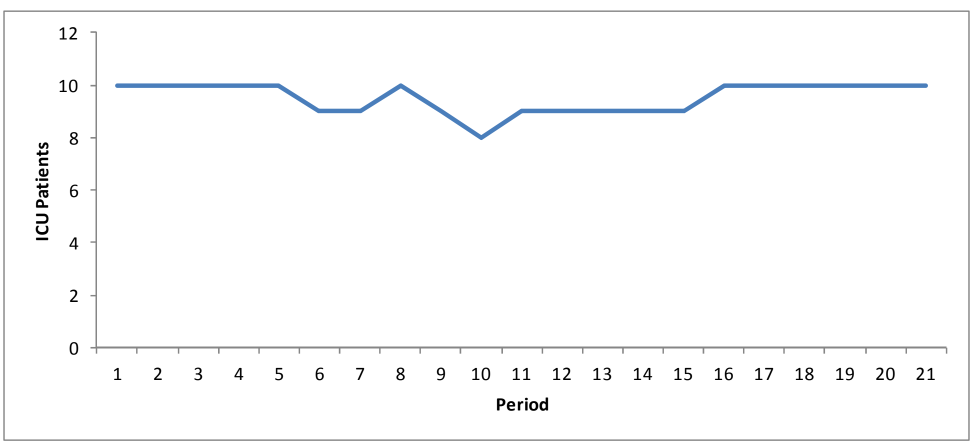

Figure 3. ICU patient population during the first week of the test runs.

This patient population forms the backdrop for the analysis. In different experiments, we superimpose one or two EVD cases on this situation and examine the effects on resource requirements and care of non-EVD patients.

The resource levels at the hospital are set so the most constraining resource is nursing staff. In the nominal condition, the available nursing staff caring for in-patients has 332 person-hours of availability during each 8-hour period (equivalent to assuming an average staffing level of 41.5 nurses at any given time). Figure 4 shows the demand for nursing staff over the first week of the model analysis, compared to the available resource level, illustrating that the nursing staff is sufficient to provide high-level care to the normal population of in-patients. The volatility in demand for nursing staff time over the first three days of the analysis period is due to the fluctuation in total in-patient population (shown in Figure 2).

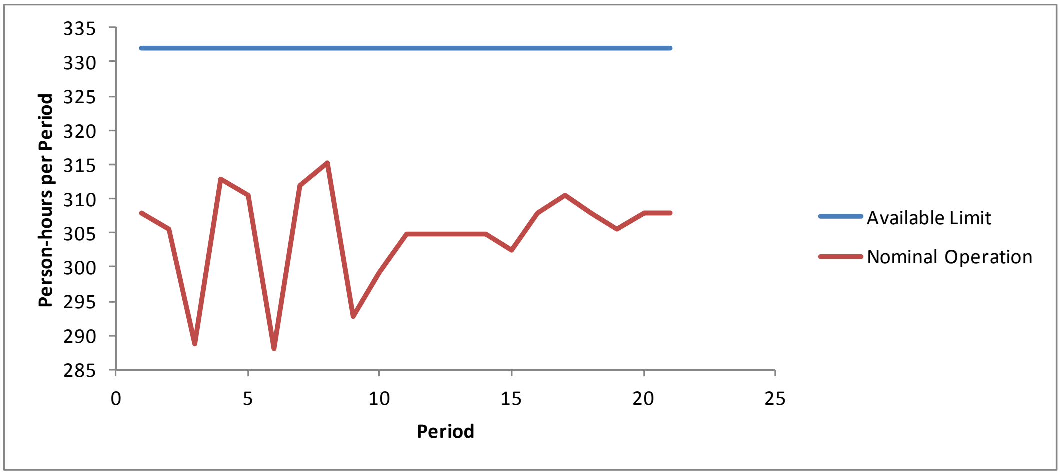

Figure 4. Nursing staff demand and availability during the first week of the test runs.

We then assume that a person with high risk of EVD presents at the Emergency Room in period 1 of the model run. In the first period, that person is treated in the ER. This includes diagnosis using rapid EVD testing in the hospital lab, services provided both by ER physicians and ID physicians, as well as nursing and tech staff in the ER. We assume the patient tests positive for EVD and is transferred to the EVD patient category and space is prepared in the ICU to accept the patient (including moving other ICU patients). Beginning in the second model period, the EVD patient is cared for using the resources of an "Ebola Team" in the hospital (physicians, nurses, lab techs, other techs, and environmental services staff trained to use the required protocols for treatment, waste disposition, etc.). The Ebola Team is drawn from the existing staff of the hospital.

We focus here particularly on the effects on the nursing staff. Figure 5 shows the demand for nursing staff time (measured in person-hours per 8-hour period) after the introduction of the EVD patient. That one additional patient with intensive care needs pushes the demand for nursing staff close to its availability limit, but the system accommodates the new demand without affecting care of other patients.

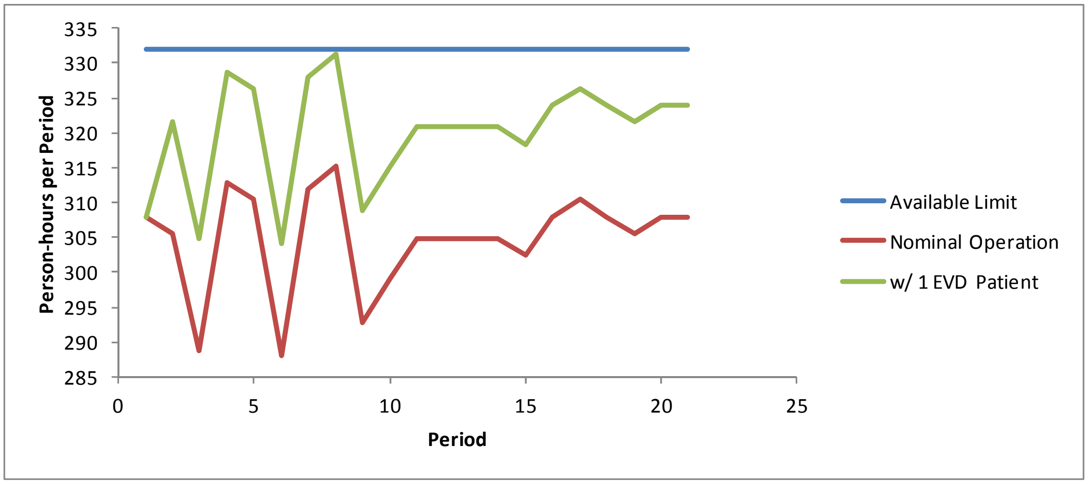

Figure 5. Nursing staff demand and availability during the first week of the test runs, with one EVD patient added to the normal patient population.

We then perform a further experiment, assuming that a second patient with high risk of EVD presents at the ER during period 4 (the beginning of day 2 in the model run). This patient is also treated for one period in the ER and then transferred to the ICU to join the first patient. The effect on the total demand for nursing staff is shown in Figure 6. The second EVD patient has a smaller marginal effect than the first (i.e., a smaller increase in demand for nursing staff) because there is some staffing associated with the presence of an EVD patient in the ICU that is not duplicated when a second patient is added. However, the addition of a second EVD patient pushed the nursing staff to its limit in several time periods across the first week.

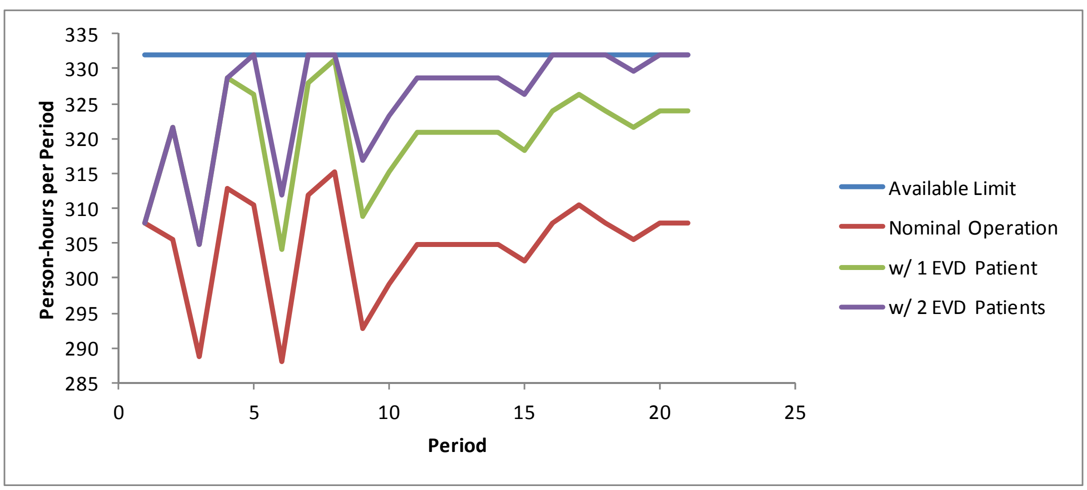

Figure 6. Nursing staff demand and availability during the first week of the test runs, with a second EVD patient added at the beginning of period 4.

When the nursing staff availability limit is reached, the overall effect is a reduction in the "nurse per patient" ratio in other units of the hospital, and the model reflects this as a reduction in a "care level score" for those patients. The model computes a score based on staffing and other resources that can be applied to each patient's care (0 = lowest; 3 = highest). Figure 7 shows the average care level score for the ICU patients that have been relocated to accommodate the EVD patients in this experiment. Note that in periods 5, 7, 8 and 17, when the nursing staff is stretched most, the care level falls somewhat.

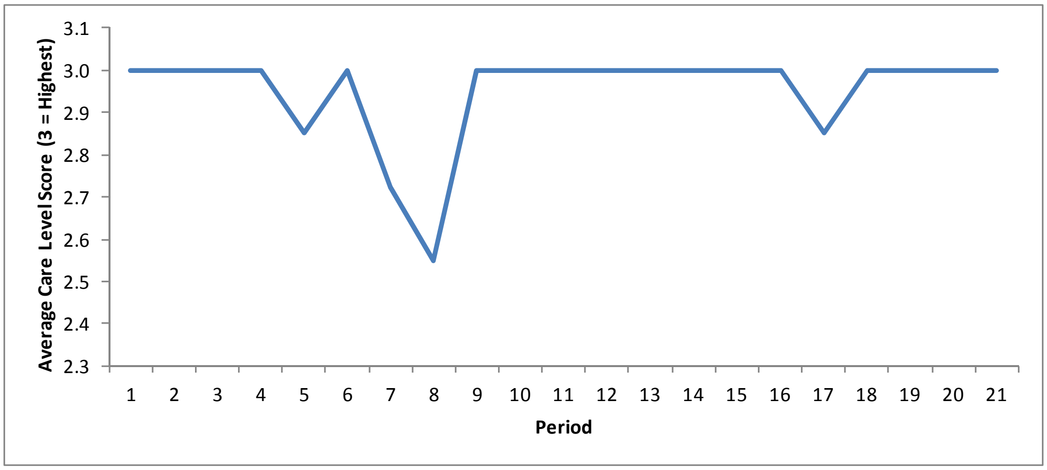

Figure 7. Average care level score for other ICU patients when a second EVD patient is added at the beginning of period 4.

This series of experiments illustrates how the model can be used to identify which resources are most limiting, and how those limitations create implications for patient care outside of the EVD patient population.

The model also traces use of other non-limiting resources, and this can be very useful for other requirements analysis. In these experiments, the availability of infectious disease (ID) physicians has been set large enough to not be a limiting constraint, but the model shows how the demand for these physicians' time changes with the introduction of one or two EVD patients. Figure 8 illustrates this for the experiments done here, with demand measured in person-hours per period. In this case, the demand for ID physicians increases the same amount for the second patient (unlike the nursing staff requirement) because the assumption in model setup for these experiments is that physician time requirement increases linearly for each EVD patient. In reality, the physician time requirement for each patient may be distributed quite unevenly over the day, but in these experiments the model is representing the demand for physician time simply as a rate per period.

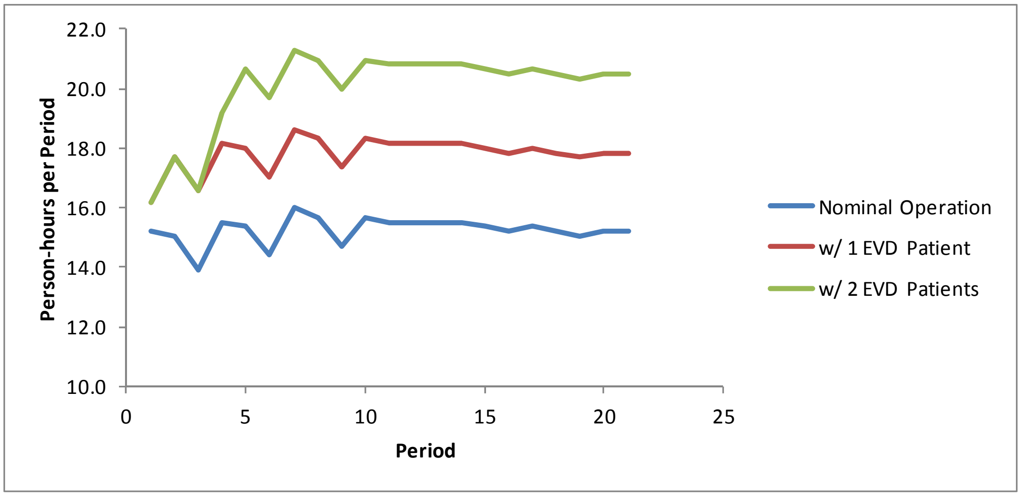

Figure 8. Requirement for ID physician hours during the first week of the model runs, with varying numbers of EVD patients.

These few experiments are relatively simple in structure, but serve to demonstrate some of the important potential uses of the model. Many other more complicated experimental scenarios could be created, and their implications explored, with the use of the model formulated here.

4 Conclusions

The focus of this paper is on resource requirements analysis for a hospital faced with treating a set of patients who have a serious infectious disease (using Ebola Virus Disease (EVD) as the illustration). Resource requirements analysis attempts to determine what resources may be needed and what adaptation strategies can be followed to allow the hospital to absorb and adapt to the situation without compromising care for other patients. This is an important application of the idea of resilience analysis for hospitals, as one of a set of critical infrastructures for our society.

A mathematical optimization model forms the basis for the analysis. This model represents the resource availability and adaptive capacities a hospital leverages to care for patients, even when stressed by an outbreak of a serious infectious disease. Section 2 describes the fundamental ideas on which the model is built, as well as the specific elements defined for the infectious disease analysis. The model is based on six types of entities: *patients*, *services*, *functions*, *resources*, *utilities* and *consumables*. These entities are related in a hierarchical way and the model allows tracing requirements for resources and adaptations (via substitution of resources, utilities and consumables) within the hospital system as it responds to needs to care for patients.

An illustrative example analysis in Section 3 demonstrates how the model might be used in a specific setting to test the ability of a hospital to respond to EVD cases. With additional investment in model enhancement and calibration for a variety of different situations, a much broader set of computational experiments could be done to explore effective strategies for hospitals to respond to a relatively large set of alternative scenarios.

5 REFERENCES

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Vugrin, E.D., D. E. Warren, and M. A. Ehlen, 2011, "A resilience assessment framework for infrastructure and economic systems: Quantitative and qualitative resilience analysis of petrochemical supply chains to a hurricane." *Process Safety Progress*, 30: 280–290.

APPENDIX: MATHEMATICAL MODEL FORMULATION

The model is a mathematical optimization that allocates available resources, utilities and consumables to best meet the needs of caring for a set of patients in various categories. Each patient category requires different services or different amounts of specific services. The appropriate set of categories for a particular analysis is defined by the model user. Levels of care allow the model to distinguish among situations in which patients receive normal care (i.e., all services required for that patient category are operating and available), levels of reduced-but-adequate care (e.g., somewhat reduced staff time per patient), or are in a non-sustainable state (i.e., some vital service cannot be provided). The set of reduced-but-adequate care levels may include several subdivisions that can be defined by the model user as appropriate for a specific application. If a total of C care levels are defined (indexed by $c = 1, 2, \dots, C$), we adopt the convention that $c = 1$ is the normal care level and $c = C$ is the non-sustainable state. States $c = 2, \dots, C-1$ are varying levels of reduced-but-adequate care.

Patients may be discharged or moved to another facility to avoid entering the non-sustainable care level. Discharges are represented as a special category of patients. The discharge category is "absorbing" (has duration at least T periods and no successor category), and patients in this category require no services. If patients must be moved to another facility, the rate at which this occurs is limited by available staff resources in the hospital, transportation resources for movement to receiving hospitals, and the ability of receiving sites to accept the evacuees.

The model is based on six types of entities: *patients*, *services*, *functions*, *resources*, *utilities* and *consumables*. These entities are related in a hierarchical way. Patients are treated by services, and these services depend on functions, resources, utilities and consumables. Each level in the hierarchy supports (either directly or indirectly) all of the levels above it. At the four lowest levels of the hierarchy, there are substitution possibilities. For example, a function may be provided using different resources, and those resources may require varying use of utilities and consumables.

To illustrate the hierarchy of entities and the substitution possibilities, consider provision of care within an ICU to a patient category that requires ventilation. This category of patients would likely be differentiated from another category of ICU patients who do not require ventilation. We might define "ICU vent care" as a service, encompassing various elements of patient care. This service requires input of functions (e.g., patient ventilation and vital signs monitoring) and some of these functions may be substitutable for one another (automatic and manual ventilation, for example). The service will also require resources (e.g., physician and nurse time, vital signs monitoring equipment), utilities (power, water), and consumables (food, oxygen, medical supplies, pharmaceuticals). At the level of functions in the hierarchy, the automatic ventilation function requires input of power, a resource (the ventilator), and substitutable consumables bulk oxygen or bottled oxygen. The manual ventilation function, which is substitutable for automatic ventilation, requires different inputs (staff time instead of power and a ventilator). A utility (e.g., generator power) may require consumables (generator fuel). It is also possible that utilities and consumables can be substituted for one another (e.g., bottled water can be substituted for water from the water lines).

With this general description as background, we can describe the model formulation in detail, using the following notation.

Decision Variables

$e_{i\tau l}(t)$	patients who have been in category i for τ periods who are evacuated to destination l during period t
$p_{ic}(t)$	total in-patients in category i and care level c at the end of period t
$P_{i\tau}(t)$	total patients in category i who have been in that category τ periods at the end of period t
$r_{kf}(t)$	usage of resource k for function f in period t
$r'_{ks}(t)$	usage of resource k for service s in period t
$\bar{r}_k(t)$	total usage of resource k in period t
$u_{jk}(t)$	usage of utility j for resource k in period t
$u'_{jf}(t)$	usage of utility j for function f in period t
$\tilde{u}_{js}(t)$	usage of utility j for service s in period t
$\bar{u}_j(t)$	total usage of utility j in period t
$v_{fs}(t)$	amount of function type f used for service s in period t
$\bar{v}_f(t)$	total required amount of function type f in period t
$w_{mj}(t)$	usage of consumable m for utility j in period t
$w'_{mk}(t)$	usage of consumable m for resource k in period t
$\tilde{w}_{mf}(t)$	usage of consumable m for function f in period t
$\hat{w}_{ms}(t)$	usage of consumable m for service s in period t
$\bar{w}_m(t)$	total usage of consumable m in period t
$W_m(t)$	amount of consumable m remaining at the end of period t
$x_{ii'}(t)$	patients who change from category i to category i' during period t
$Y_s(t)$	required amount of services of type s in period t

Input Data

$a_i(t)$	arrivals of patients in category i during period t
$B_i(t)$	available capacity for patients in category i during period t
$E_l(t)$	upper bound for evacuating patients to destination location l in period t
$p_{ic}(0)$	initial in-patients in category i and care level c at the beginning of the analysis period
$R_k(t)$	amount of resource k available during period t (in appropriate units)
S_{il}	available capacity for evacuated patients in category i at destination location l

$U_j(t)$ amount of utility *j* available during period *t* (in appropriate units)

$W_m(0)$ initial amount of consumable commodity *m* available

$\Delta_m(t)$ quantity of consumable commodity *m* delivered in period *t*

Parameters and Coefficients

g_m cost of a unit of consumable commodity *m*

h_j cost of a unit of utility *j*

$i'(i)$ successor category for patients leaving category *i*

α_{js} units of utility *j* required to provide one unit of service *s*

β_{fs} units of function *f* required to provide one unit of service *s*

γ_i duration (number of periods) that a patient remains in category *i*

δ_{mj} units of consumable commodity *m* required to provide one unit of utility *j*

η_{mk} units of consumable commodity *m* required to provide one unit of resource *k*

λ_k cost of a unit of resource *k*

ω_{mf} units of consumable commodity *m* required to provide one unit of function *f*

ϕ_{ms} units of consumable commodity *m* required to provide one unit of service *s*

σ_{jk} units of utility *j* required to provide one unit of resource *k*

τ_{jf} units of utility *j* required to provide one unit of function *f*

θ_{kf} units of resource *k* required to provide one unit of function *f*

ξ_{ks} units of resource *k* required to provide one unit of service *s*

ρ_{sic} required amount of service *s* for a patient in category *i* and care level *c* (per period)

ζ_{si} required amount of service *s* for evacuating a patient in category *i*

π_{ic} penalty cost for a patient in category *i* in care level *c*, with $\pi_{ic} < \pi_{ic'}$ if $c < c'$

ψ_{il} penalty cost for evacuating a patient in category *i* to destination *l*

The model formulation reflects changes in system status over time. The beginning of the analysis horizon is defined to be time $t = 0$. The planning horizon is divided into a set of *T* discrete periods, each of length *h* hours, and these periods are indexed by $t = 1,\ldots,T$. Some variables (e.g., patients in-care or stocks of consumable items) are defined as "snapshots" at specific points in time while others (e.g., patients evacuated, resources consumed, etc.) reflect activity during the interval corresponding to one of the discrete periods. Thus, $t = 1$ can refer to either the first time period or the time at the end of that period. Values at $t = 0$ are assumed to be the initial conditions. With these conventions, all the variables can be defined consistently.

The complete model statement is as follows:

$$\text{Min} \sum_i \sum_c \sum_t \pi_{ic} p_{ic}(t) + \sum_i \sum_l \psi_{il} \sum_t \sum_{\tau=1}^{\gamma_i} e_{i\tau l}(t) + \sum_k \sum_t \lambda_k \overline{r}_k(t) + \sum_j \sum_t h_j \overline{u}_m(t) + \sum_m \sum_t g_m \overline{w}_m(t) \qquad (1)$$

s.t. $$P_{i1}(t) = a_i(t) + \sum_{i'' \in O(i)} P_{i''\gamma_{i''}}(t-1) - \sum_l e_{i1l}(t) \qquad \textit{for all } i,t \qquad (2)$$

$$P_{i\tau}(t) = P_{i,\tau-1}(t-1) - \sum_l e_{i\tau l}(t) \qquad \textit{for all } i,t;\ \tau = 2,\dots,\gamma_i \qquad (3)$$

$$\sum_{\tau=1}^{\gamma_i} P_{i\tau}(t) = \sum_c p_{ic}(t) \qquad \textit{for all } i,t \qquad (4)$$

$$\sum_{\tau=1}^{\gamma_i} P_{i\tau}(t) \le B_i(t) \qquad \textit{for all } i,t \qquad (5)$$

$$\sum_t \sum_{\tau=1}^{\gamma_i} e_{i\tau l}(t) \le S_{il} \qquad \textit{for all } i,l \qquad (6)$$

$$\sum_i \sum_{\tau=1}^{\gamma_i} e_{i\tau l}(t) \le E_l(t) \qquad \textit{for all } l,t \qquad (7)$$

$$Y_s(t) = \sum_i \sum_c \rho_{sic} p_{ic}(t) + \sum_i \zeta_{si} \sum_l \sum_{\tau=1}^{\gamma_i} e_{i\tau l}(t) \qquad \textit{for all } s,t \qquad (8)$$

$$\sum_{g' \in G_{ns}^f} \left[\frac{v_{g's}(t)}{\beta_{g's}} \right] = Y_s(t) \qquad \textit{for all sets } G_{ns}^f, \ \textit{for all } s,t \qquad (9)$$

$$\overline{v}_f(t) = \sum_s v_{fs}(t) \qquad \textit{for all } f,t \qquad (10)$$

$$\sum_{g' \in G_{ns}^r} \left[\frac{r'_{g's}(t)}{\xi_{g's}} \right] = Y_s(t) \qquad \textit{for all sets } G_{ns}^r, \ \textit{for all } s,t \qquad (11)$$

$$\sum_{g' \in G^r_{nf}} \left[\frac{r_{g'f}(t)}{\theta_{g'f}} \right] = \overline{v}_f(t) \qquad \textit{for all sets } G^r_{nf}, \;\; \textit{for all } f,t \tag{12}$$

$$\overline{r}_k(t) = \sum_s r'_{ks}(t) + \sum_f r_{kf}(t) \qquad \textit{for all } k,t \tag{13}$$

$$\overline{r}_k(t) \le R_k(t) \qquad \textit{for all } k,t \tag{14}$$

$$\sum_{g' \in G'^c_{ns}} \left[\frac{\widehat{w}_{g's}(t)}{\phi_{g's}} \right] + \sum_{g'' \in G''^c_{ns}} \left[\frac{\tilde{u}_{g''s}(t)}{\alpha_{g''s}} \right] = Y_s(t) \qquad \textit{for all sets } G^c_{ns}, \;\; \textit{for all } s,t \tag{15}$$

$$\sum_{g' \in G'^c_{nf}} \left[\frac{\tilde{w}_{g'f}(t)}{\omega_{g'f}} \right] + \sum_{g'' \in G''^c_{nf}} \left[\frac{u'_{g''f}(t)}{\tau_{g''f}} \right] = \overline{v}_f(t) \qquad \textit{for all sets } G^c_{nf}, \;\; \textit{for all } f,t \tag{16}$$

$$\sum_{g' \in G'^c_{nk}} \left[\frac{w'_{g'k}(t)}{\eta_{g'k}} \right] + \sum_{g'' \in G''^c_{nk}} \left[\frac{u_{g''k}(t)}{\sigma_{g''k}} \right] = \overline{r}_k(t) \qquad \textit{for all sets } G^c_{nk}, \;\; \textit{for all } k,t \tag{17}$$

$$\overline{u}_j(t) = \sum_s \tilde{u}_{js}(t) + \sum_f u'_{jf}(t) + \sum_k u_{jk}(t) \qquad \textit{for all } j,t \tag{18}$$

$$\overline{u}_j(t) \le U_j(t) \qquad \textit{for all } j,t \tag{19}$$

$$w_{mj}(t) = \delta_{mj}\, \overline{u}_j(t) \qquad \textit{for all } m,j,t \tag{20}$$

$$\overline{w}_m(t) = \sum_s \widehat{w}_{ms}(t) + \sum_f \tilde{w}_{mf}(t) + \sum_k w'_{mk}(t) + \sum_j w_{mj}(t) \qquad \textit{for all } m,t \tag{21}$$

$$W_m(t) = W_m(t-1) - \overline{w}_m(t) + \Delta_m(t) \qquad \textit{for all } m,t \tag{22}$$

$$\textit{all variables} \ge 0 \;\; \textit{and } e_{i\tau l}(t) \;\; \textit{integer}, \quad \textit{for all } i,l,t;\; \tau = 1,\ldots,\gamma_i \tag{23}$$

The model allocates consumables and resources in a way that first attempts to keep all patients in the highest care level possible in all time periods. This is done through use of penalty coefficients π_{ic} in the objective function. A penalty (ψ_{il}) is also associated with patients evacuated ($e_{i\tau l}(t)$), so that patients will remain in the system unless there are insufficient consumables and resources to provide adequate care for them. Cost coefficients (λ_k , h_j , g_m) are also attached to the usage of consumables, utilities and resources so that the solution allocates only as much as is required in each time period. In any particular model run, it is assumed that the model user has specified these relative costs and penalties in a way that reflects the user's preferences on how tradeoffs are made. As part of an overall analysis, it is likely to be important to explore various combinations of these values to determine how the solution changes as a function of these input parameters, and to use that sensitivity information to guide overall planning decisions.

Constraints (2)-(7) account for patients and their movements. The patient variables drive consumption of services, functions, resources, utilities and consumables. These constraints take the form of requirement equations and limits, as represented in eqs. (8)-(22).

Constraint (8) reflects the required services of type *s*. The model allows substitutions among elements to meet the requirements at higher levels in the overall hierarchy. For example, different functions can be substituted for the provision of services (e.g., either a ventilator or manual bagging can provide the service of ventilation for a patient). Similarly, different resources may be substitutable in the production of either functions or services. At the lower levels of the hierarchy, a more complex set of substitution possibilities is present among consumables and utilities (e.g., the consumable bottled water can be substituted for the water lines utility). To accommodate the substitution possibilities, it is necessary to have variables that track the allocation of consumables, utilities, functions and resources to the hierarchical elements above them.

It is also necessary to define sets of substitutable elements at various levels, and there may be multiple (mutually exclusive) sets for a given result. For example, power sources are substitutable for functions and services, as are sources of potable water. However, the power sources are not substitutable for the water sources. To manage this, a collection of *groups* are defined for use in constraints (9)-(17):

- G^f_{ns} : the n^{th} group of functions that are substitutable for production of service *s*
- G^r_{nf} : the n^{th} group of resources that are substitutable for production of function *f*
- G^r_{ns} : the n^{th} group of resources that are substitutable for production of service *s*
- G^c_{ns} : the n^{th} group of consumables and utilities that are substitutable for production of service *s*
- G^c_{nf} : the n^{th} group of consumables and utilities that are substitutable for production of function *f*
- G^c_{nk} : the n^{th} group of consumables and utilities that are substitutable for production of resource *k*

In constraint (9), the individual terms in the summation represent how much of the service requirements are met by each of the substitutable functions. For functions that are not substitutable in production of service *s*, the associated substitution group has only one element and the summation on the left side of eq. (9) has only one term. The total required amount of function f is expressed in constraint (10). A parallel structure for resources is reflected in constraints (11) for service production and (12) for function production, with constraint (13) representing total resource requirements and constraint (14) the limits on available resources.

For consumables and utilities, the sets G_{ns}^{c}, G_{nf}^{c}, and G_{nk}^{c} may contain both consumables and utilities, making it necessary to do the summations over the entries corresponding to each type of element. We define $G_{n\,s}^{\prime c}$ as the set of consumable entries in G_{ns}^{c}, and $G_{ns}^{\prime\prime c}$ as the set of utility entries in G_{ns}^{c}. Definitions of $G_{nf}^{\prime c}$, $G_{nf}^{\prime\prime c}$, $G_{nk}^{\prime c}$ and $G_{nk}^{\prime\prime c}$ are parallel. The substitution constraints for production of services are written in constraint (15); constraints (16) and (17) represent parallel structures for use of consumables and utilities for functions and resources. Total usage of utilities is represented in constraint (18), and the limitation on available utilities is in constraint (19).

Consumables can be required for some utilities (e.g., generator fuel for generator power), but the model assumes that consumables used in this way are not substitutable, so eq. (20) represents that use. The total use for each type of consumable is defined by constraint (21) and constraint (22) tracks the available stocks of consumables so that usage in each period cannot exceed the amount available (as a result of non-negativity requirements).

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